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EVALUATION OF A SIMPLE METHOD FOR COLOR MONITOR RECALIBRATION

13

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CONTENTS

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SUMMARY

An algorithm for recalibrating a color monitor's RGB input-output relations is evaluated, that requires only a single measurement of an appropriately chosen reference stimulus.
Three sets of data were obtained for evaluating the algorithm's error reduction power. These relate to different ways in which the monitor can get out of calibration. That is, slow (but cumulative) changes over time, fast changes due to gun interacton (resulting from changed stimulus conditions), and error introduced by a different setting of the monitor's brightness control.
The algorithm was found to be quite effective in dealing with the instantaneous calibration changes (gun interaction, brightness control), and also for keeping track of the slow changes that may finally necessitate a full recalibration of the monitor.

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Evaluatie van een eenvoudige methode voor het herijken van een kleurenmonitor

M.P. Lucassen en J. Walraven

SAMENVATTING

Er werd een eenvoudig algoritme ontwikkeld voor het snel herijken van de RGB input-output relaties van een kleurenmonitor. Daarvoor is slechts één meting nodig van een goed gekozen, op het betreffende beeld afgestemde, referentie stimulus.

Het algoritme werd geëvalueerd met drie sets van meetgegevens, die betrekking hebben op de verschillende manieren waarop de monitor ontregeld kan raken. Dat zijn respectievelijk langzame (maar in de tijd cumulatieve) veranderingen, snelle veranderingen als gevolg van "overspraak" tussen de kleurkanonnen (optredend bij wijziging van het beeld) en de fouten die ontstaan door verandering van de helderheidsafstelling van de monitor.

Gebleken is dat het recalibratie-algoritme goed voldoet voor het corrigeren van de ontregeling als gevolg van stimulusverandering of helderheidsinstelling. Daarnaast is het ook geschikt voor het bijhouden van de geleidelijke veranderingen, die uiteindelijk tot een volledige monitor calibratie aanleiding kunnen geven.

1 INTRODUCTION

Computer controlled CRT's are used for a wide range of applications, from displaying text to complex animated graphics. In this case the CRT was used as stimulus generator for experiments in the context of an ESPRIT II sponsored project on the optimization of (colored) image quality (ADOT, 1989). Typical for this purpose is the need for a well-defined input-output calibration, i.e. the relation between the CRT's digital input (digital to analog converter value, DAC value) and the screen's light output (luminance) for each of the three R,G,B guns.

When a computer controlled color monitor has been calibrated for a certain stimulus configuration, there is no guarantee that after a period of time, or after a change of configuration, the calibration is still valid. Depending on the application, display hardware and photometric equipment, many adjustments may be needed to reach the desired accuracy for color reproduction.

Recently, several authors reported their findings from monitor calibration efforts (Cowan, 1983, 1986; Post and Calhoun, 1987, 1989; Brainard, 1989). Post and Calhoun compared seven models for generating colors with specific CIE chromaticity coordinates and luminances on CRT's. They conclude that a piecewise linear interpolation method is most accurate, and found that 16 calibration points per gun are sufficient to reconstruct the input-output relation. However, their work does not solve the common problems of gun interaction and temporal instability. Brainard focussed on finding a minimal set of assumptions, including assumptions of RGB interaction and spatial (pixel) interaction, that limit the number of measurement points for monitor calibration.

A full monitor calibration can be very time consuming, so it is worthwhile to find out when recalibration really becomes necessary. For most applications, a "measure and adjust" algorithm as proposed by Post and Calhoun may be used, but again, this involves a lot of measurements.

In this communication we report on the results obtained with a recalibration algorithm that reduces measurements to a minimum. We found that, for a given stimulus condition, a single measurement, i.e. the measurement of the average stimulus chromaticity (usually white) at an intermediate luminance level, may already result in an acceptable recalibration. Recalibration here means shifting the R,G,B input-

output relations along the log luminance axis. The chromaticity coordinates of the monitor's phosphors are assumed to remain constant (as was also confirmed by measurement). In the following we shall present data that show both the need for continuous calibration and the efficacy of the method proposed.

2 METHOD

2.1 Colorimetry

In principle, that is, assuming additive color mixing to apply, one only needs the input-output relations (luminance vs. DAC value) and the three phosphor chromaticity coordinates to calculate the DAC values (0-255) for the red, green and blue gun, required for producing specified XYZ (CIE 1931) tristimulus values. The colorimetric equation for deriving the monitor's luminance outputs (R,G,B,) is given by

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} x_R/y_R & x_G/y_G & x_B/y_B \\ 1 & 1 & 1 \\ z_R/y_R & z_G/y_G & z_B/y_B \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (1)$$

where x,y and z are the 1931 CIE chromaticity coordinates with sub-scripts R,G,B referring to the appropriate phosphor. The assumption of phosphor constancy implies that the matrix in (eq. 1) has fixed elements. Note the conversion sign on the matrix. The DAC values for the three guns are obtained from

$$\begin{bmatrix} DAC_R \\ DAC_R \\ DAC_B \end{bmatrix} = \text{INTERPOLATION} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (2)$$

where the INTERPOLATION operation stands for interpolating the input-output curve on a logaritmic scale.

A smaller interpolation error results this way, because the logaritmic input-ouput curves show less curvature than the linear curves. Applying (eq. 2) after (eq. 1) will be referred to as "generating" colors, whereas applying the inverse of (eq. 1) after the inverse of (eq. 2) will be referred to as "analyzing" colors. Thus, "generating" involves transforming XYZ to RGB space, whereas "analyzing" implies the opposite transformation.

2.2 Measuring the input-output relation

Before a recalibration algorithm can be used, the original set of RGB input-output relations must be known. The monitor we used was a high resolution Hitachi 19 inch color monitor (1152x900 pixels, 24 bit/-pixel), controlled by a Sun 3/260 computer. Measurements of the CRT's light output were performed with a SpectraScan PR-702AM (Photo Research) spectroradiometer and a Spectra Pritchard (Photo Research) photometer. The photometer was used for measuring at low luminance levels.

Fig. 1a shows the input-output relations, measured at the center of the screen (using the calibration pattern, discussed below), whereas Fig. 1b shows the same measurements six months later. Anticipating the results to be discussed in the next section, it is clear that the monitor's calibration curves changed quite a bit over time (especially at the lower DAC values). This might be due to aging of the phosphors, although we found, confirming Brainard (1989), that their chromaticity coordinates had hardly changed. We initially measured, at the highest DAC values (255), the following set of (x,y) values for R, G and B: (0.631, 0.355), (0.306 0.596), (0.147, 0.070) whereas 6 months later we obtained: (0.633, 0.355), (0.307, 0.598), (0.146, 0.070).

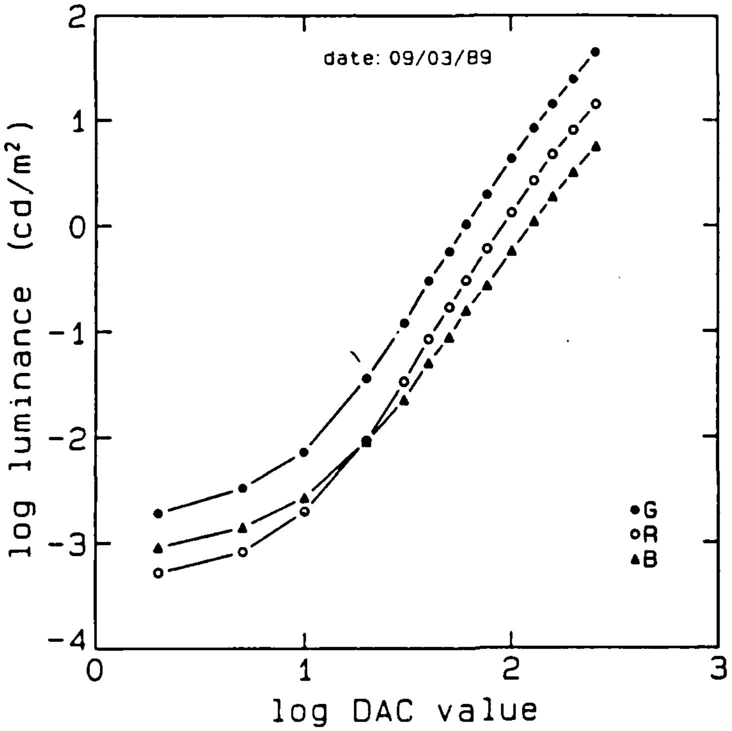

Fig. 1a Luminance vs DAC-value characteristics measured at installation date.

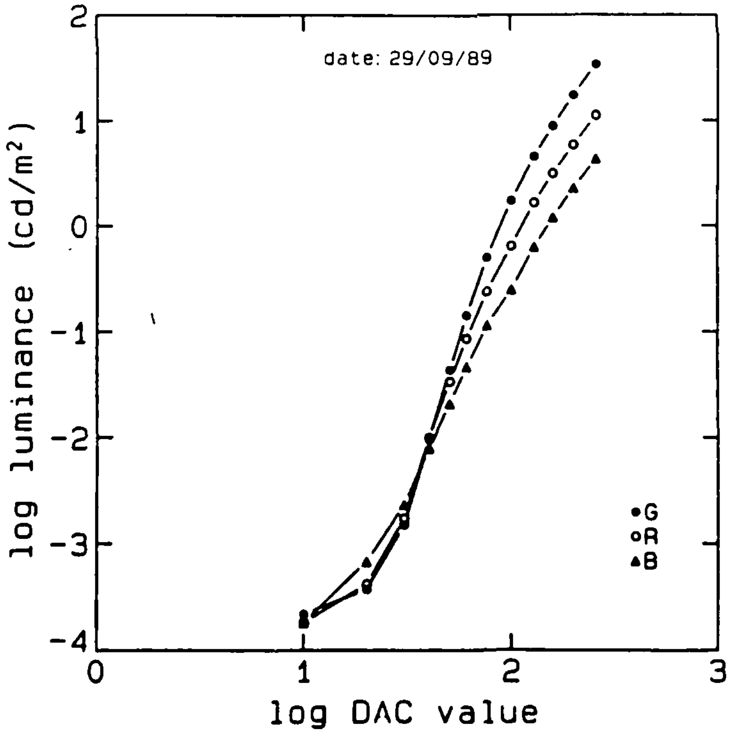

Fig. 1b The same curves measured after about 6 months of display use.

Following the practice recommended by Cowan (1986) and Brainard (1989), the calibration pattern we used, (spatially) resembled the test pattern that was used for testing both screen inhomogeneity and gun interaction. Here, the calibration pattern consisted of 35 square patches (70x70 pixels) separated by a black grid. The DAC values were chosen so as to produce roughly equal intervals on a logarithmic scale. Each R,G,B curve was measured while the other two guns were disconnected, to exclude residual contributions of the two other guns (McManus and Hoffman, 1985; Walraven, 1988).

Note that, on a log-log scale, the input-output relations show an almost linear relationship for the greater part of the DAC values that are used. This is the more or less expected result, considering the exponential relationship between gun voltage and beam current.
Apart from long term variations in screen luminance, also short term effects, like those following a stimulus change (gun interaction), may alter the input-output relations. These are the more day-to-day calibration problems that ask for a simple recalibration procedure.

2.3 The recalibration algorithm

When colors are generated on a CRT screen, in a configuration that is quite different from the one used for calibrating the display, the screen voltage may not remain constant and thus affect the R,G,B beam currents. Other effects may have to be considered as well, but, whatever the mechanisms involved, the net result is a change in the input-output relation. In other words, loading the DAC values calculated from (eq. 1) and (eq. 2) may not produce the desired luminances R,G and B. The basic idea behind the recalibration algorithm is to compensate for such effects that is, in as far as they can be treated as gain changes in the DAC-to-luminance conversion. The adjustment consists of a vertical shift (offset) of the three input-output curves (on a logaritmic scale), consistent with a scaling of the luminance (R,G,B). The adjustments are made on the basis of a single reference, i.e. an achromatic stimulus (D_{65}) of medium luminance, presented in the center of the screen.

The recalibration procedure thus requires three steps:

1. Generate the white reference stimulus (x_0,y_0,Y_0) using (1) and (2), and determine the required phosphor luminances, R_0, G_0 and B_0.

2. Measure the reference stimulus (x,y,Y) which will probably deviate from its nominal values (x_0, y_0, Y_0), and calculate the required phosphor luminances, R, G and B.

3. Calculate the correction factors C_R, C_G and C_B, (using $C_R=R_0/R$ etc.) and correct the luminances R,G,B of the original input-output curves accordingly. That is, the original input-output relations have their outputs R,G and B divided by the factors C_R, C_G and C_B, respectively.

3 EVALUATION

The recalibration algorithm was evaluated in the course of psychophysical studies on color vision (effect of color contrast on visual acuity). Its main purpose was to correct for the gun interaction that occurred when changing from a dark background (as used for calibration) to the light backgrounds used for the stimulus pattern. In addition, the calibration provided information over the gradual change in the light output of the monitor.

In order to test the precision of the recalibration, 20 colors, located on two different loci of equal Munsell Chroma (see Fig. 2), were presented successively in the center of a 35-patch test pattern. The chromaticities (x,y) and luminances (Y) of the colors were measured with the spectroradiometer, and then compared with their nominal values (x_0, y_0, Y_0). The chromatic error, Δxy, and percent luminance error, $\% \Delta Y$, were calculated with

$$\Delta xy = \sqrt{(x_0 - x)^2 + (y_0 - y)^2}, \tag{3}$$

$$\% |\Delta Y| = 100\ |Y_0 - Y|/Y_0. \tag{4}$$

The errors were calculated for the set of test colors, when generated either with the original set of calibration functions or with the recalibrated functions.

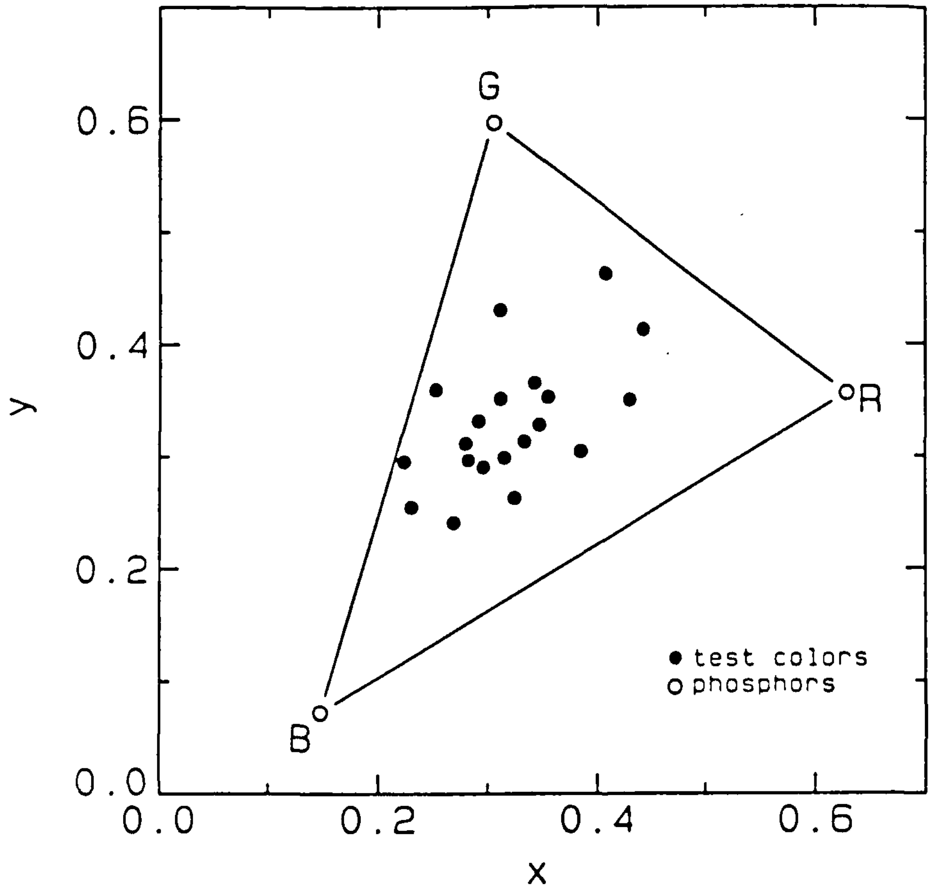

Fig. 2 Chromaticities (x,y) of the 20 test colors used for evaluating the recalibration algorithm.

The recalibration algorithm was evaluated for three different sets of data. The first set (Set 1) relates to the situation where the same input-output curves are still used after a year's monitor use. It turned out, as shown already in Fig. 1, that over this period of time the gradual changes in the monitor had culminated in quite a drastic departure from its original input-output characteristics. The second set (Set 2) relates to the standard usage of the algorithm, that is, with up-to-date calibration curves, but not necessary applicable to the experimental condition in question (i.e. light background, rather than the dark background used during calibration). In the third set (Set 3) the data were generated in a condition where the brightness control of the monitor was deliberately changed. This is the kind of error that may be introduced when the monitor has different users and/or has to be used at different (screen) brightness levels.

The results obtained in the three test conditions are shown in Table I. What is shown is a comparison of the average error and standard deviation of the 20 test colors when using either the original or recalibrated (scaled) RGB input-output curves.

The results of Table I are plotted in Fig. 3. Note that the error reduction for data sets 2 and 3 is mainly in the luminance direction and that, exactly for that reason, the effect of recalibration is quite effective, reducing the error by 15% and 30%, respectively. The small change in chromatic error is reflected in roughly equal scale factors for R,G and B (see Table I).

Table I Comparison of mean error and standard deviation of 20 test colors, either without RGB recalibration (scale factors 1.00) or with RGB recalibration (scale factor variable).

Data set	scale factor			$\%\|\Delta Y\|$		Δxy	
	R	G	B	mean	sd	mean	sd
1	1.00	1.00	1.00	54.18	1.65	0.0265	0.0123
	1.95	2.45	2.16	31.37	5.13	0.0163	0.0094
2	1.00	1.00	1.00	15.04	0.84	0.0028	0.0019
	1.18	1.17	1.19	0.63	0.55	0.0031	0.0016
3	1.00	1.00	1.00	35.66	0.99	0.0106	0.0057
	1.53	1.54	1.52	5.15	1.21	0.0088	0.0046

The error reduction for the data of Set 1 is large in both the luminance and chromatic direction and the remaining errors cannot be neglected. Note (in Table I) that the scale factors are quite different now for R, G and B. This is the expected result in view of the change in shape of the input-output curves over a six month period. Whether such errors are allowed depends on the application. Often, chromatic

errors are compared with the size of a MacAdams ellipse, which provides an estimate of the minimum error due to the limitations of the visual system. On the basis of tabulated MacAdam ellipses (Wyszecki and Stiles, 1982), we obtained a rough estimate of the average minimum error in the chromaticty space covered by the color monitor. Considering only the error in the direction of the major axis of the ellipses, we arrived at an average (Δxy) of 0.005.

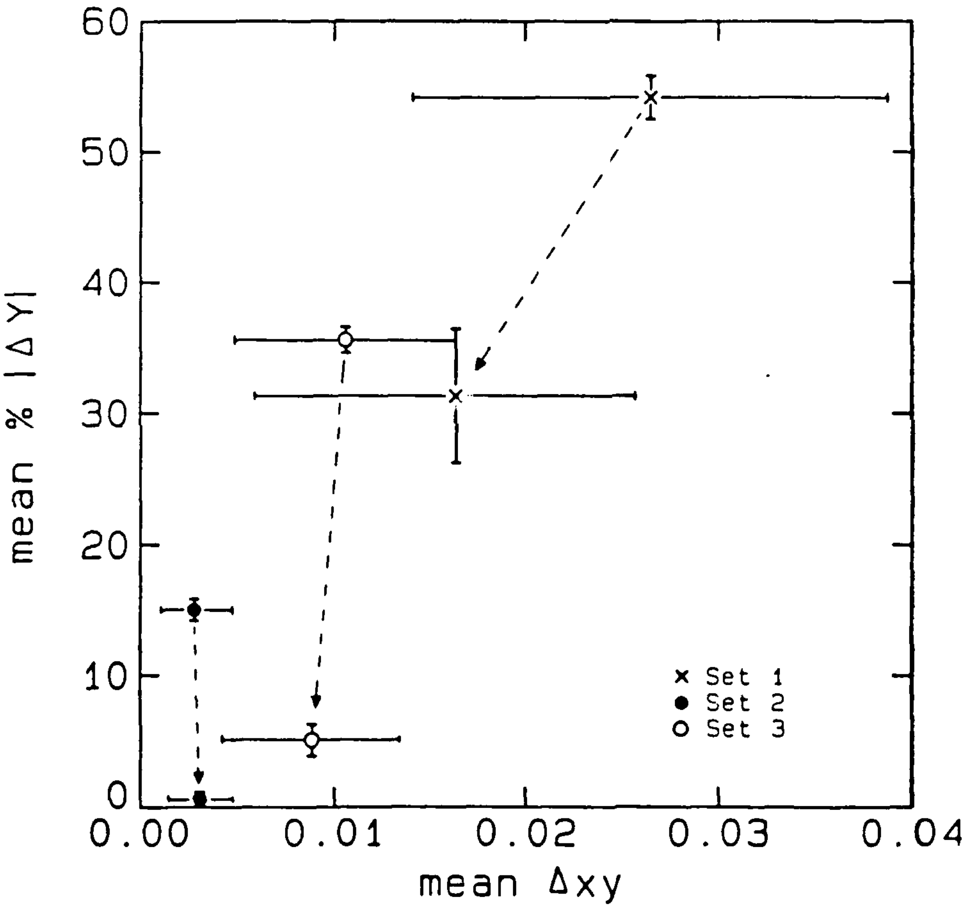

Fig. 3 Means and standard deviations for chromatic (Δxy) and luminance (ΔY) errors, measured with and without the recalibration algorithm (data from Table I). The dashed arrows indicate the error reduction due to the recalibration algorithm.

This means that, for Sets 2 and 3, the accuracy of color reproduction (obtained with interpolation of the input-ouput curve and the recalibration algorithm) can be in the order of a just perceptible chromat-

icity difference. On the other hand, the data from Set 1 show that a full monitor recalibration is necessary.

So far we have not considered the problem of the spatial inhomogeneity of the screen luminance. Even expensive, high resolution monitors are not free from such inhomogeneities, as can be seen in Fig. 4.

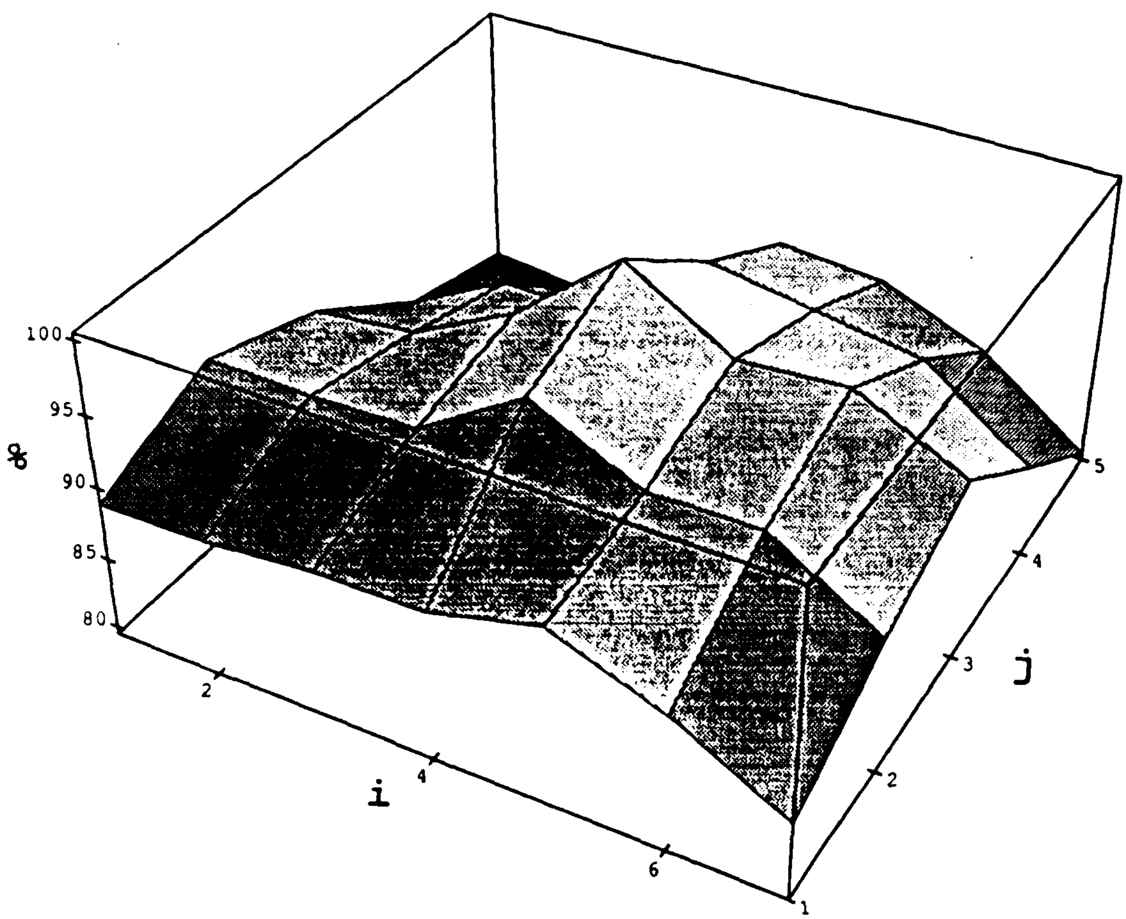

Fig. 4 Relative screen luminance (%), measured at the centers of the 35 patches of the calibration/stimulus grid. These centers are located at the crossing points (i,j) of a 5 x 7 grid. The center of the screen is located at (i,j)=(4,3). The total area sampled by this grid measures 25.5 x 17.5 cm.

In this figure the luminances plotted are measured at the center of each square of our calibration pattern. These centers are located at the crossing points of the i,j grid. Note that at the boundary of the sampled screen area the luminance falls off to about 20% of the maxi-

mum found in the center. Fortunately, these spatial variations proved to be almost identical for the three guns. This means that we are dealing only with luminance variations, the kind of error that can be easily handled by the recalibration algorithm.

4 DISCUSSION

The simple recalibration algorithm we proposed turned out to be well suited for the purpose it was developed for, that is, compensating for non-additivity of the (separately measured) color guns. In general, this method is only suitable for correcting errors, that can be described in terms of vertical translation of the log RGB vs DAC value functions. It is of interest though, that our results show that this is the kind of error that is likely to be encountered on a CRT display.

If, in the course of time, the algorithm shows error reduction to be less complete, this is a warning signal. Values from 1.1 to 1.2 are normally found, but when the scale factors become too divergent a full monitor recalibration is needed. This is illustrated by the data of Set 1, which relate to the condition where the shape of the input-output curves had changed with time. So, regularly checking the scale factors is also effective to discover slow drifts in the monitor's output.

The fact that the scale factors are greater than 1, means that the measured output is less than would be expected from the calculations. Several factors (e.g. phosphor aging, gun interaction) may contribute to this loss in effective output, but these are nevertheless handled by the simple scaling procedure of the recalibration algorithm. This is particularly helpful when different stimulus configurations, requiring different correction factors, have to be displayed. The fact that a single measurement (of the reference white) was found to be sufficient for the recalibration procedure, does not necessarily apply to all stimulus conditions. However, if it does, as can be tested in the way we have shown, much time and effort can be saved in maintaining accurate stimulus control in complex stimulus scenarios. Moreover, measuring just a single white point on the screen, can be done with a simple (but reliable) chromaticity meter, which is much less expensive and cumbersome than using the spectroradiometer that would be needed for measuring colored stimuli.

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